High Energy Neutrinos from Blazars

Misaligned blazars

by

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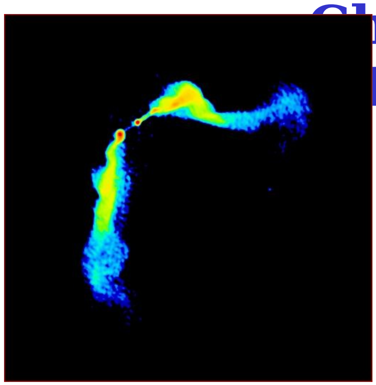
ICRC proceedings;
Gamma 2001 procs
astro-ph;
submitted to PRL

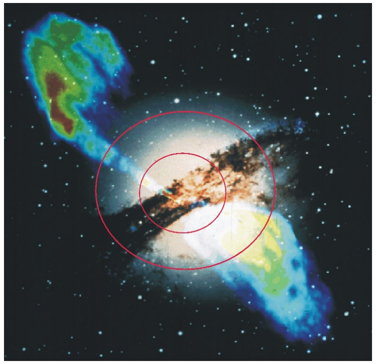
3C 465



FR I

Blazars:
Nonthermal particles
Intense photon fields

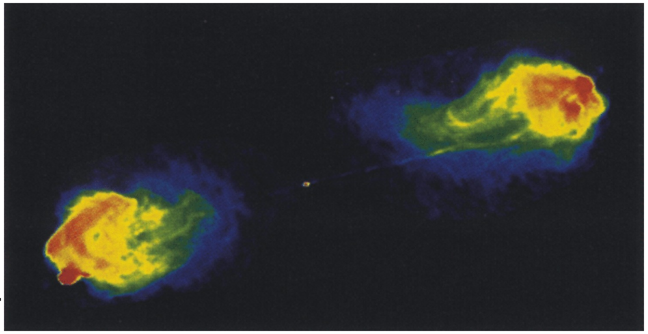
FR Is



Cen A

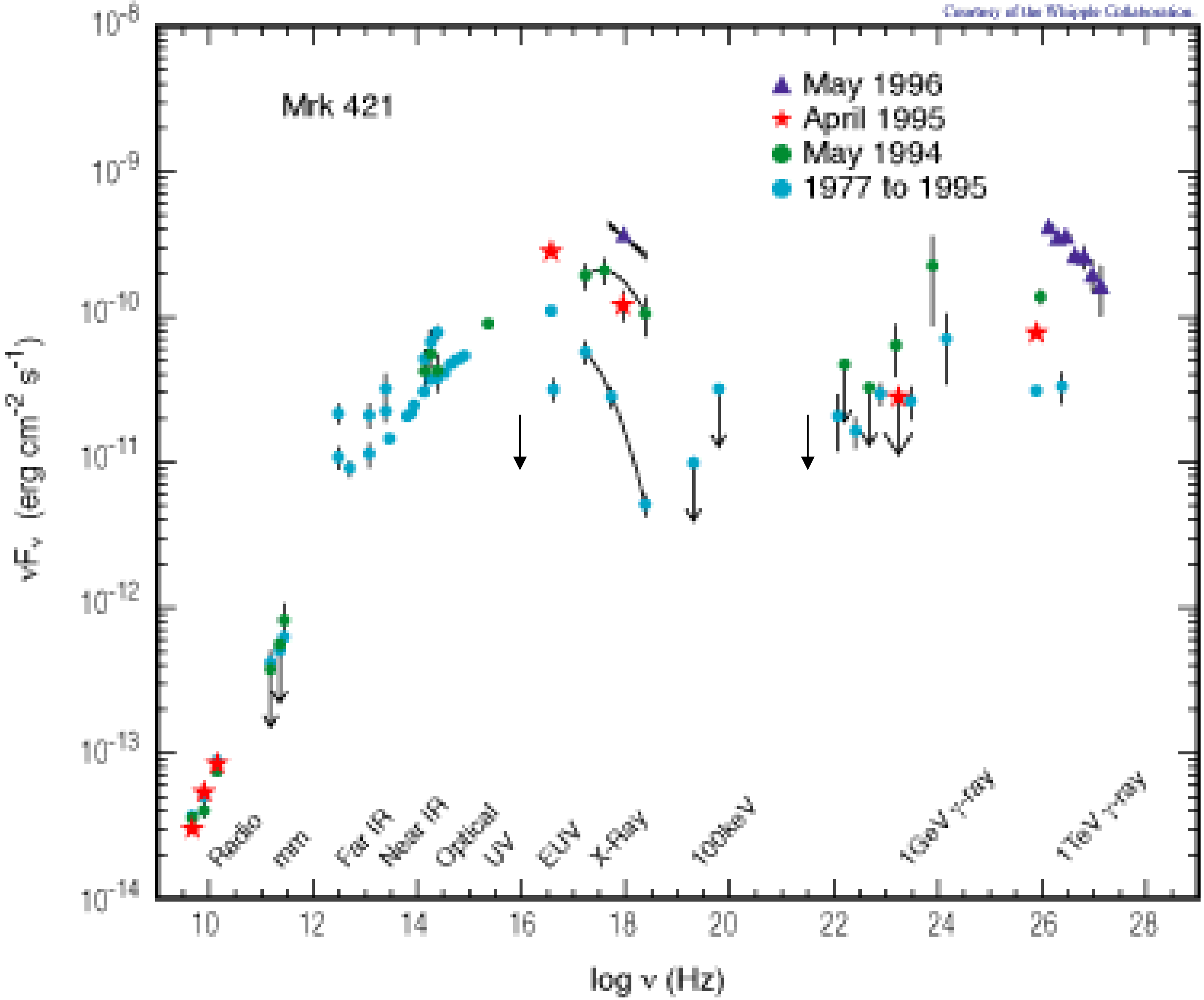
Outline

- **Spectral energy distributions of blazars**
- **Importance of external radiation field for photomeson production in FSRQs**
- **Calculations of neutrinos from protons/ions in blazars (3C 279 parameters)**
- **Formation of jets in FR I and FRII radio galaxies: importance**



FR II

Cyg A



Macomb + 1996

HBL Lac: Mrk 421

$z = 0.031$

$d_L = 4.4\text{x}10^{26}$ cm

Apparent isotropic gamma-ray luminosity: $\sim 10^{45}\ f_{-10}$ ergs s^{-1}

Variability timescale at TeV energies: ~ 15 min

HBL Mrk 501

z = 0.033

$d_L \approx 150$ Mpc

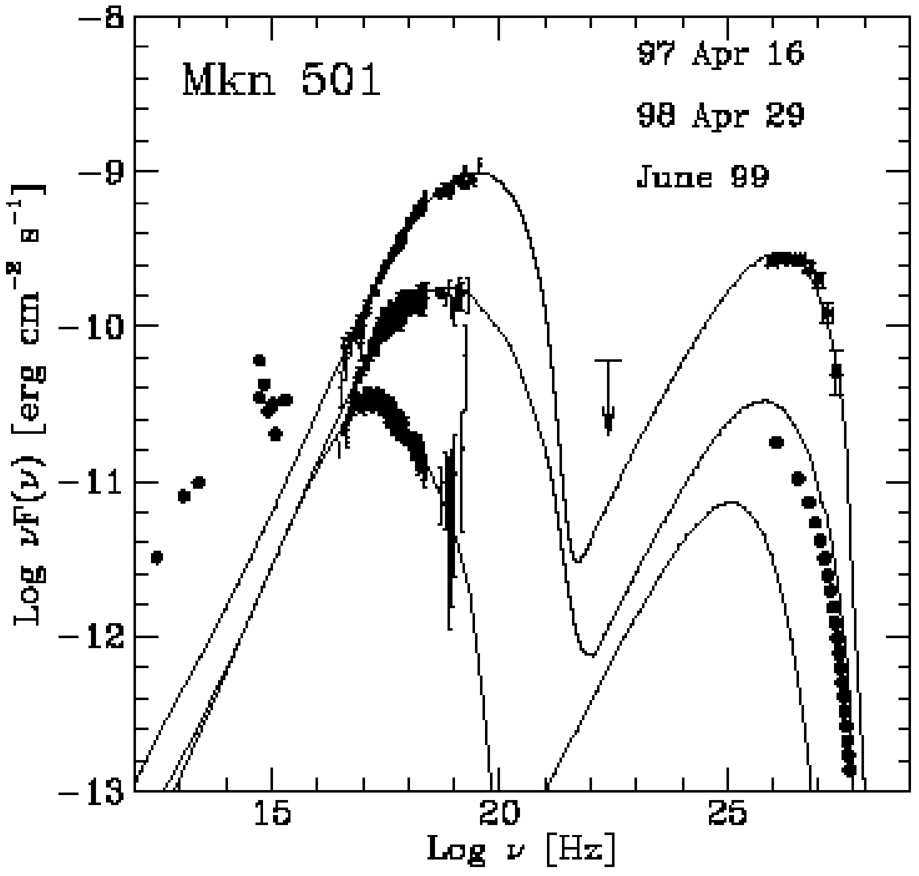
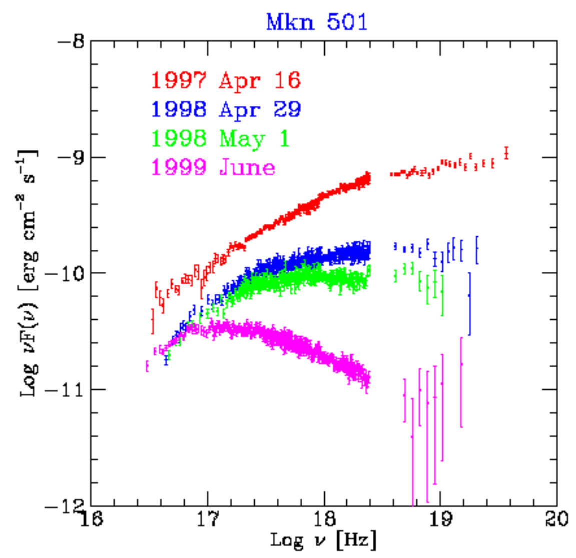


FIG. 7.—Overall SED of Mrk 501 of 1997 April 16, 1998 April 29, and 1999 June. The solid line is the spectrum calculated with the homogeneous SSC model described in the text. The filled circles are from the HEGRA 1998–1999 data (from Aharonian et al. 2001).

Gamma-ray luminosity:
~10^{45} f_{-10} ergs s^{-1}

Variability timescale at TeV energies: < 1 day



Maraschi and Tavecchio 2001

FSRQ 3C 279

Maraschi and Tavecchio 2001

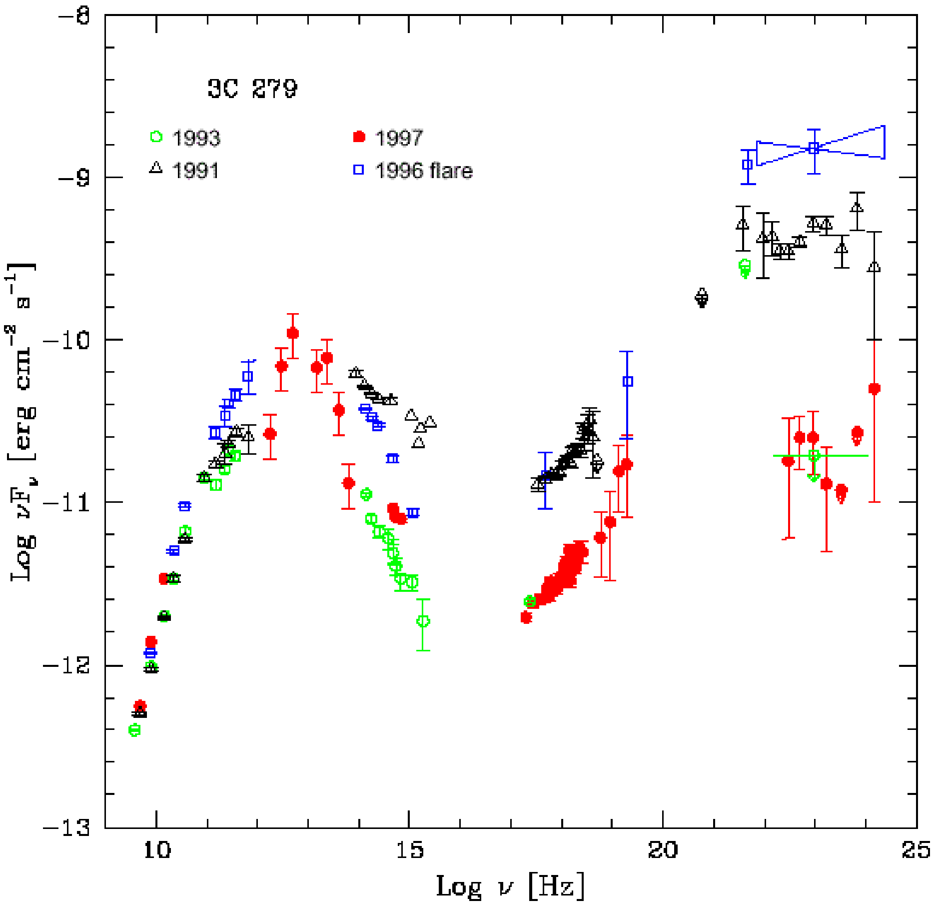


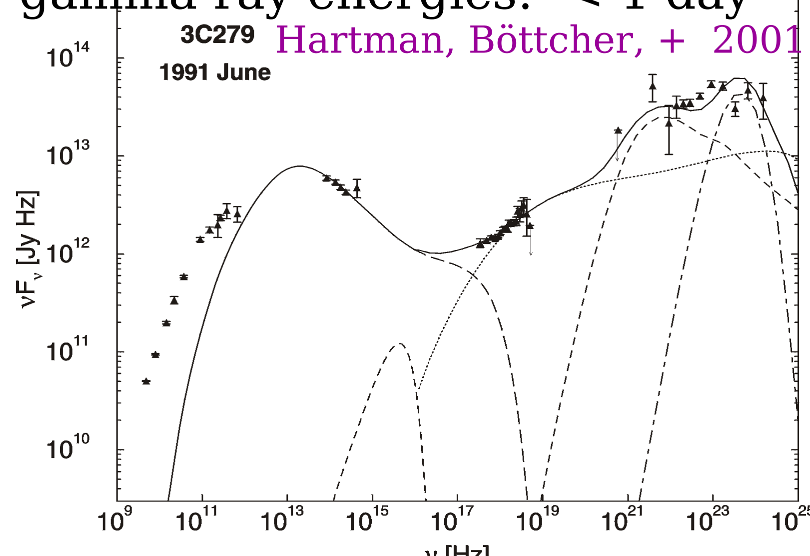
Figure 2. Quasi-simultaneous SEDs of the quasar 3C279 taken in the different epochs. The *Beppo*SAX and EGRET data taken in 1997 are almost exactly contemporaneous, while the ISO spectrum is taken one month before.

$z = 0.538$, $d_L = 1.03\text{x}10^{28}$ cm

Gamma-ray luminosity (ergs s^{-1}):
~$5\text{x}10^{48}$ x (f/10^{-9} ergs cm^{-2} s^{-1}) ergs s^{-1}

Variability timescale at gamma-ray energies: < 1 day

Hartman, Böttcher, + 2001



Require multiple components to fit SED

Radiation Physics

$$u'_{\nu'} = \frac{4\pi d_L^2 (\nu F_\nu)}{\delta^4 (2\pi r_b^2 c)} = \frac{L_\nu}{\delta^4 (2\pi r_b^2 c)}; \nu' = \frac{(1+z)\nu}{\delta}$$

$$r_b = \frac{c t_{\mathrm{var}} \delta}{(1+z)}; \delta = [\Gamma(1-\beta\cos\theta)]^{-1}$$

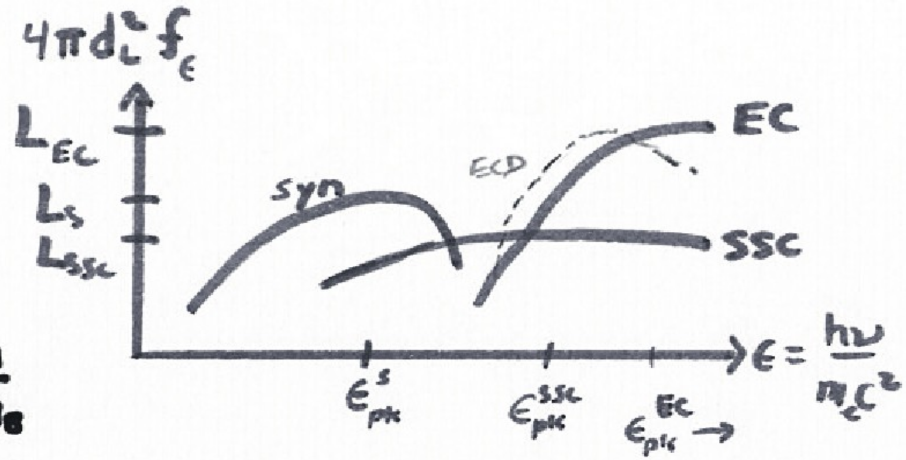
$$\Rightarrow u'_{\nu'} \propto \delta^{-6}$$

difficulties for neutrino production

with synchrotron field

Spectral Components

$$\frac{L_{EC}}{L_s} \approx \frac{u'_{ext}}{u_B} = \frac{\delta^2 u_{ext}}{u_B}$$

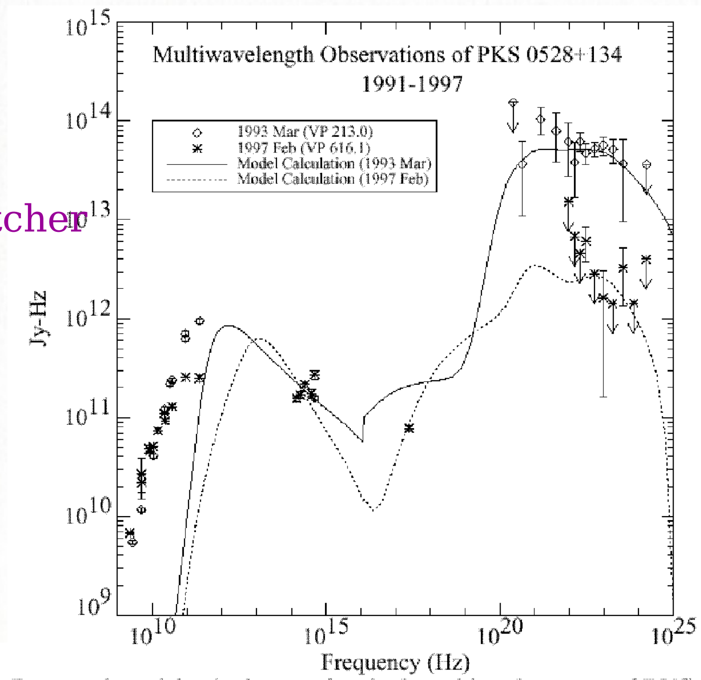


$$\frac{L_{ssc}}{L_s} \approx \frac{u'_s}{u_B} \approx \frac{L_s}{2\pi r_b^2 c \delta^4}\,\frac{1}{u_B}$$

$$\therefore \frac{L_{ssc}}{L_{EC}} = \frac{L_s}{2\pi r_b^2 c\, \delta^4}\,\frac{1}{\delta^2 u_{ext}} \Rightarrow u'_{ext} \cong \frac{a L_s}{2\pi r_b^2 c \delta^4}$$

$$a \equiv L_{EC}/L_{ssc}$$

model fit by Böttcher



$$u'_{ext,\nu'} = a u'_{syn,\nu'}$$

$$\nu' \approx \delta \nu_{ext}$$

Magnetic Field and Doppler Factor Estimates

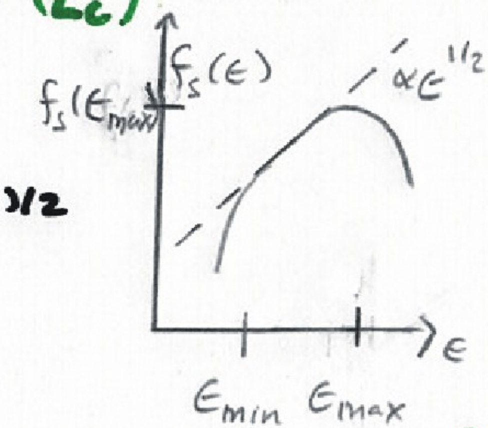
(i) Direct Observations

$$u_{ph}' = u_s' + u_{ext}' \simeq u_B (L_C/L_s) = \frac{L_{EC} + L_{SSC}}{L_s}$$

$$u_B = \frac{L_s}{L_C} u_s' \left(1 + \frac{u_{ext}'}{u_s'}\right) = (1+a)\frac{L_s}{L_C} u_s' = \frac{(1+a)}{2\pi r_b^2 c}\frac{L_s^2}{L_C}\delta^4$$

$$B \simeq \frac{2(1+z)\sqrt{1+a}}{c\,\delta^3\, t_{var}} \left(\frac{L_s}{c}\right)^{1/2} \left(\frac{L_s}{L_C}\right)^{1/2} \propto \delta^{-3}$$

(ii) Equipartition

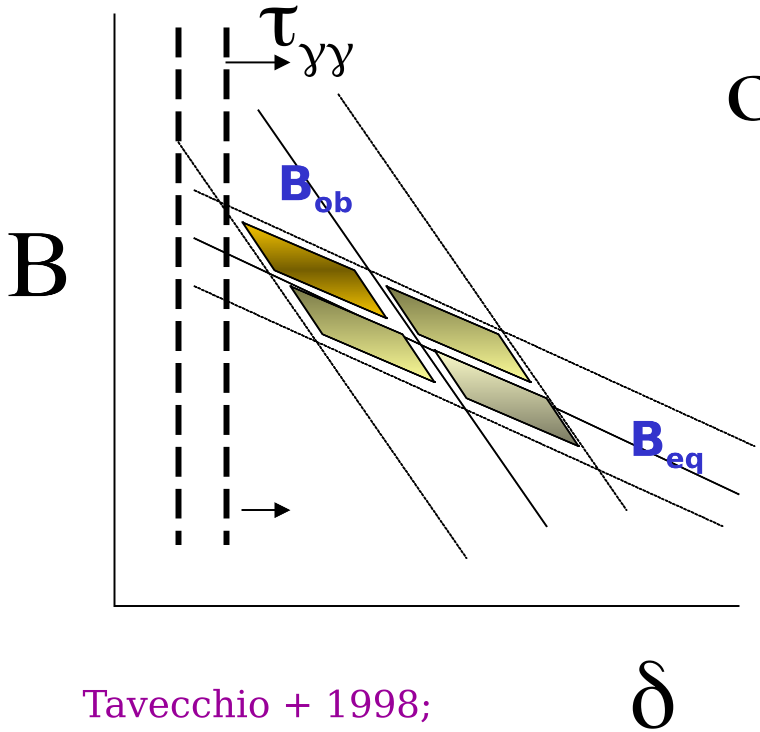


$$f_s(\epsilon) \simeq \frac{\delta^4 u_B c \sigma_T}{6\pi d_L^2}\left[\frac{(1+z)\epsilon}{\delta \epsilon_B}\right]^{(3-p)/2}$$

$$\eta \equiv (1+k_{pe})\frac{u_e}{u_B}$$

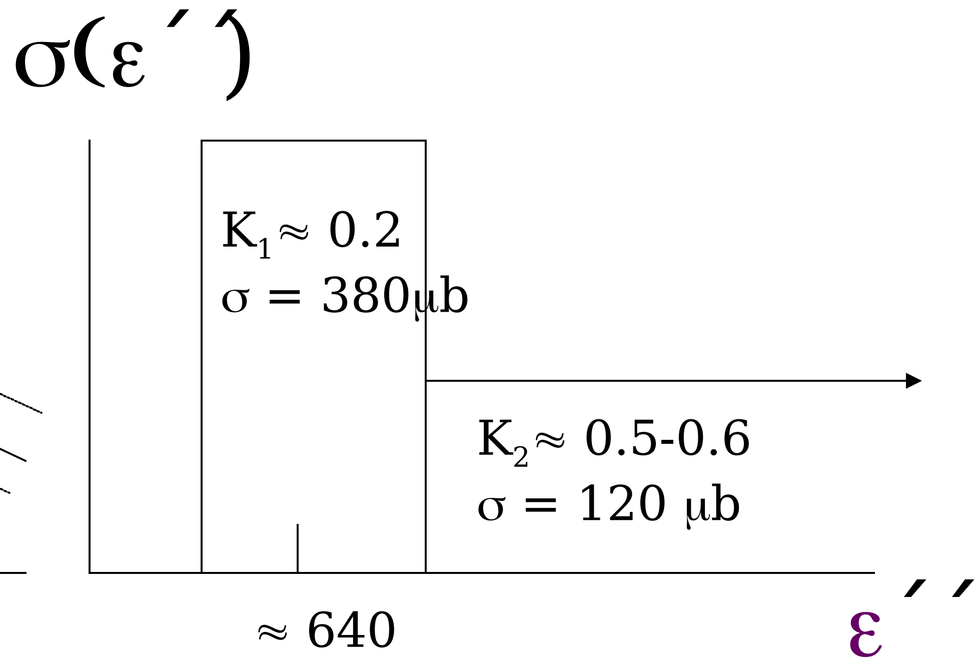
(in Gauss) $$B_{eq} \cong \frac{90(1+z)^{5/7}}{\delta^{13/7}\,[t_{var}(d)]^{6/7}}\left[\frac{d_{28}^2 (1+k_{pe}) f_{-10} \ln(\epsilon_{max}/\epsilon_{min})}{\eta\, \epsilon_{-6}^{1/2}}\right]^{2/7}$$

B and δ



Tavecchio + 1998;
Atoyan and Dermer
200

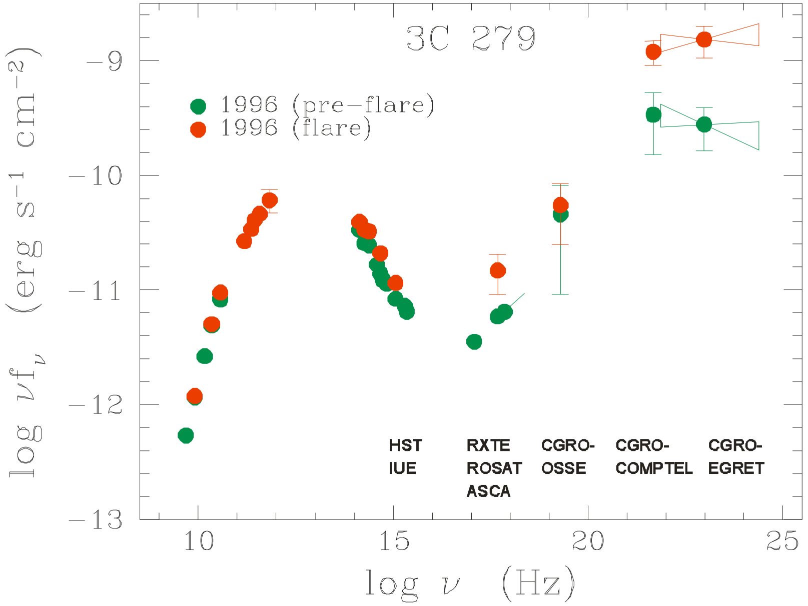
Photomeson Neutrino Production Calculations



Compare with Muecke et al. (1999)

$$t_{\mathrm{p}\gamma}^{-1}(\gamma_p) = \int_{\frac{\epsilon_{\mathrm{th}}}{2\gamma_p}}^{\infty} d\epsilon' \, \frac{c\, n'_{\mathrm{ph}}(\epsilon')}{2\gamma_p^2 \epsilon'^2} \int_{\epsilon_{\mathrm{th}}}^{2\epsilon'\gamma_p} d\epsilon_{\mathrm{r}} \, \sigma(\epsilon_{\mathrm{r}}) K_{\mathrm{p}\gamma}(\epsilon_{\mathrm{r}}) \epsilon_{\mathrm{r}} \ ,$$

Nonthermal Proton Spectrum



$$L_p = 2\times 10^{48}\delta^4 \, ergs\,s^{-1}$$

$$N_p(\gamma_p) \propto \gamma_p^{-2}$$

$$r_L = (3.1\times 10^6 cm)\gamma_p^{\max}/B(G) < r_b$$

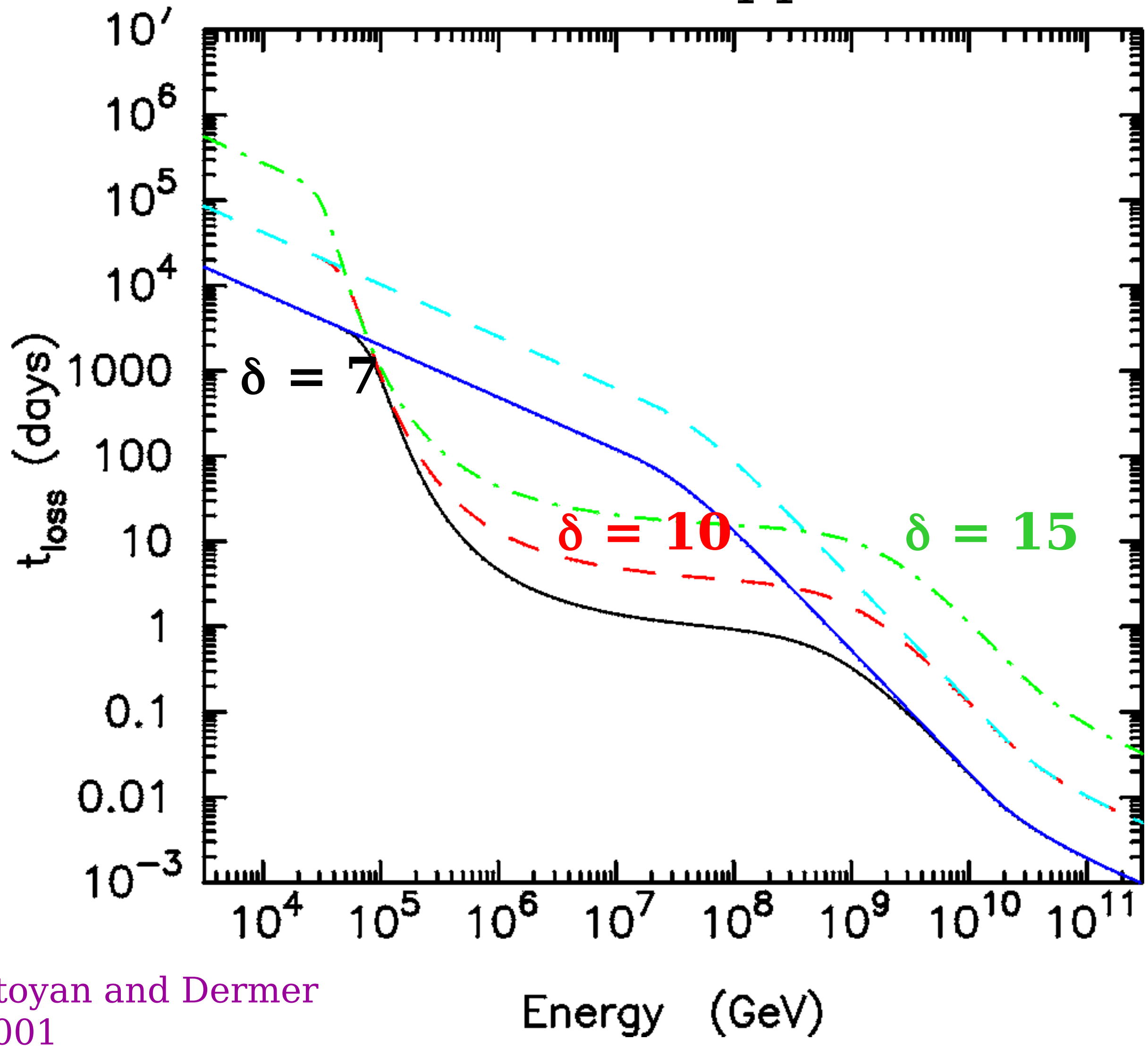
$$\Rightarrow E_p << 10^{18} - 10^{19} eV$$

Proton power based on 3-week average spectral fluxes from 3C 279 in 1996 (Wehrle et al. 1998)

- Corresponds to average γ–ray luminosity measured from 3C 279
- Unlikely to produce UHECRs in the inner jets of blazars
- Cosmic-ray bound of Waxman and Bahcall does not apply to neutrino production from blazars

Photomeson production energy-loss timescale

Different Doppler factors

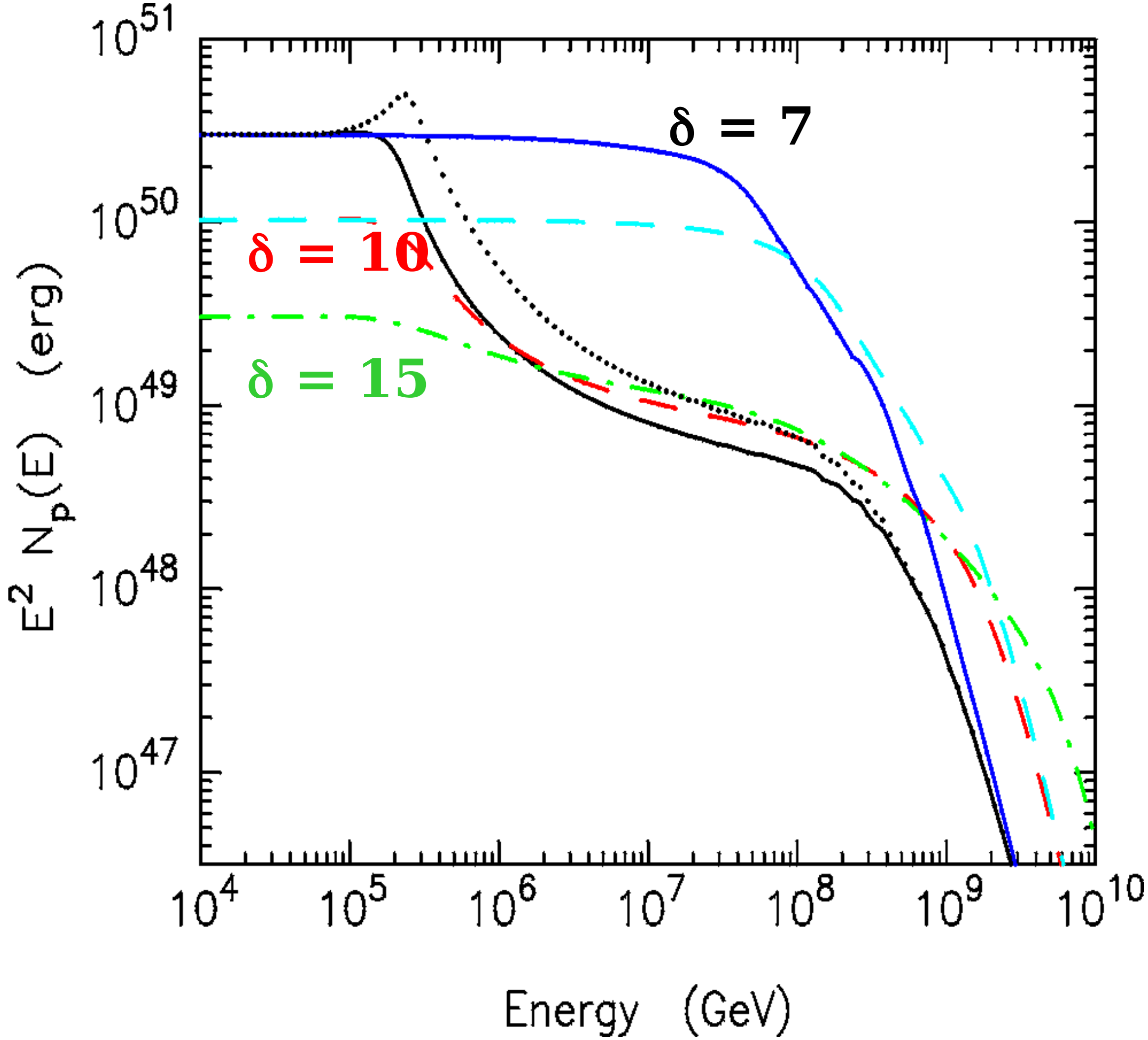


- photomeson energy-loss timescales in observer frame for properties, using 1996 3C 279 paramers (Wehrle et al. 1998)

Atoyan and Dermer 2001

Energy Distributions of Relativistic Protons

Different Doppler factors



Proton distribution after 3 weeks, with and without external field

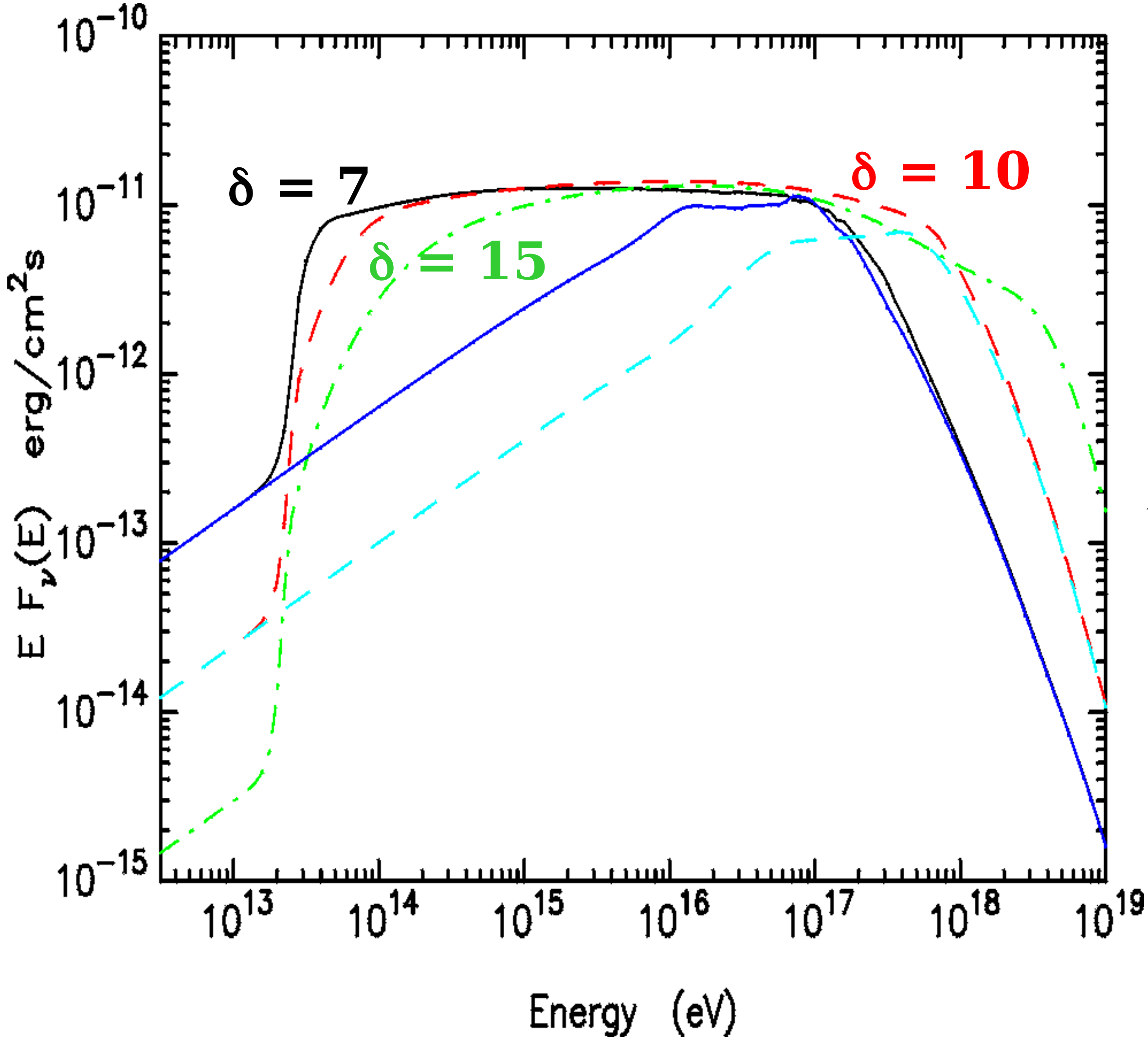
Dots: no neutron escape

$$p + \gamma \rightarrow n + \pi^+$$

Nonthermal proton accumulation

3-week average Neutrino Fluxes

Different Doppler factors



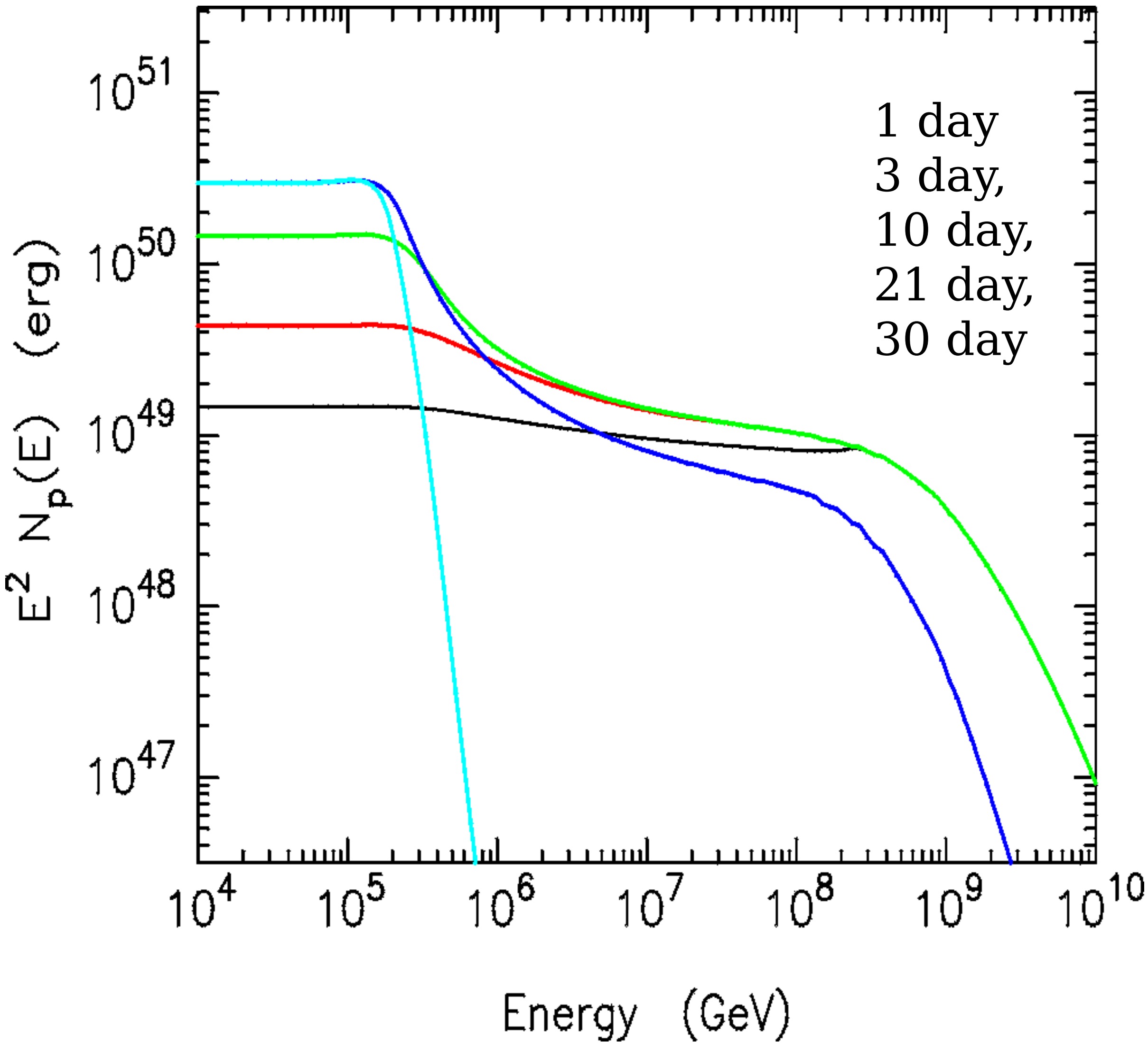
- Neutrino fluxes from 3C 279 based on 3-week average spectral fluxes observed in 1996 (Wehrle + 1998), with t_{var} = 1 day
- Compare average γ-ray fluxes observed during this time:

≈ 5x10^{-10} ergs cm^{-2} s^{-1}

- >~ 1-2% efficiency in neutrinos compared to γ rays
- what is k_{pe}?

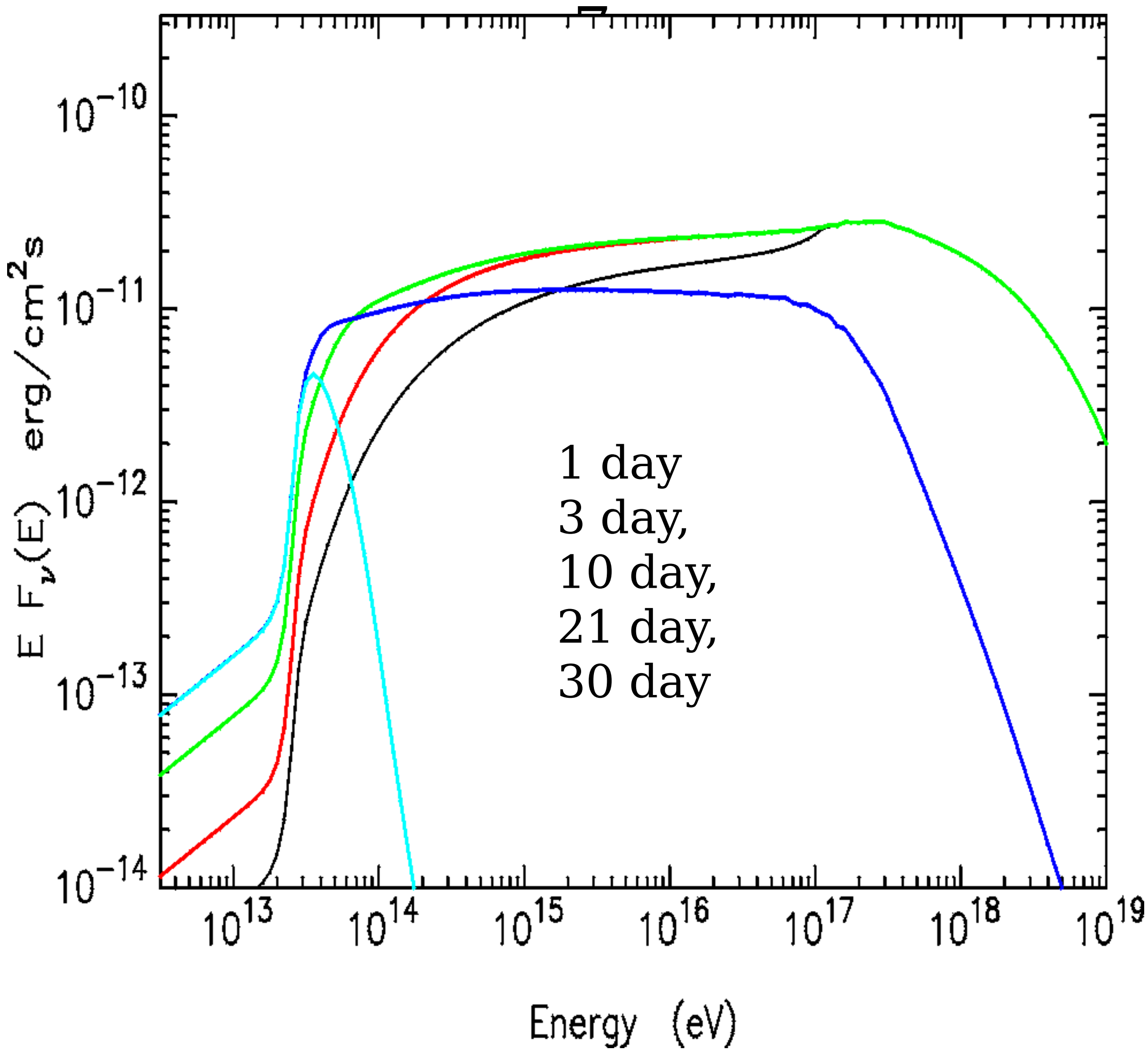
Evolution of the proton distribution

$\delta = 7$



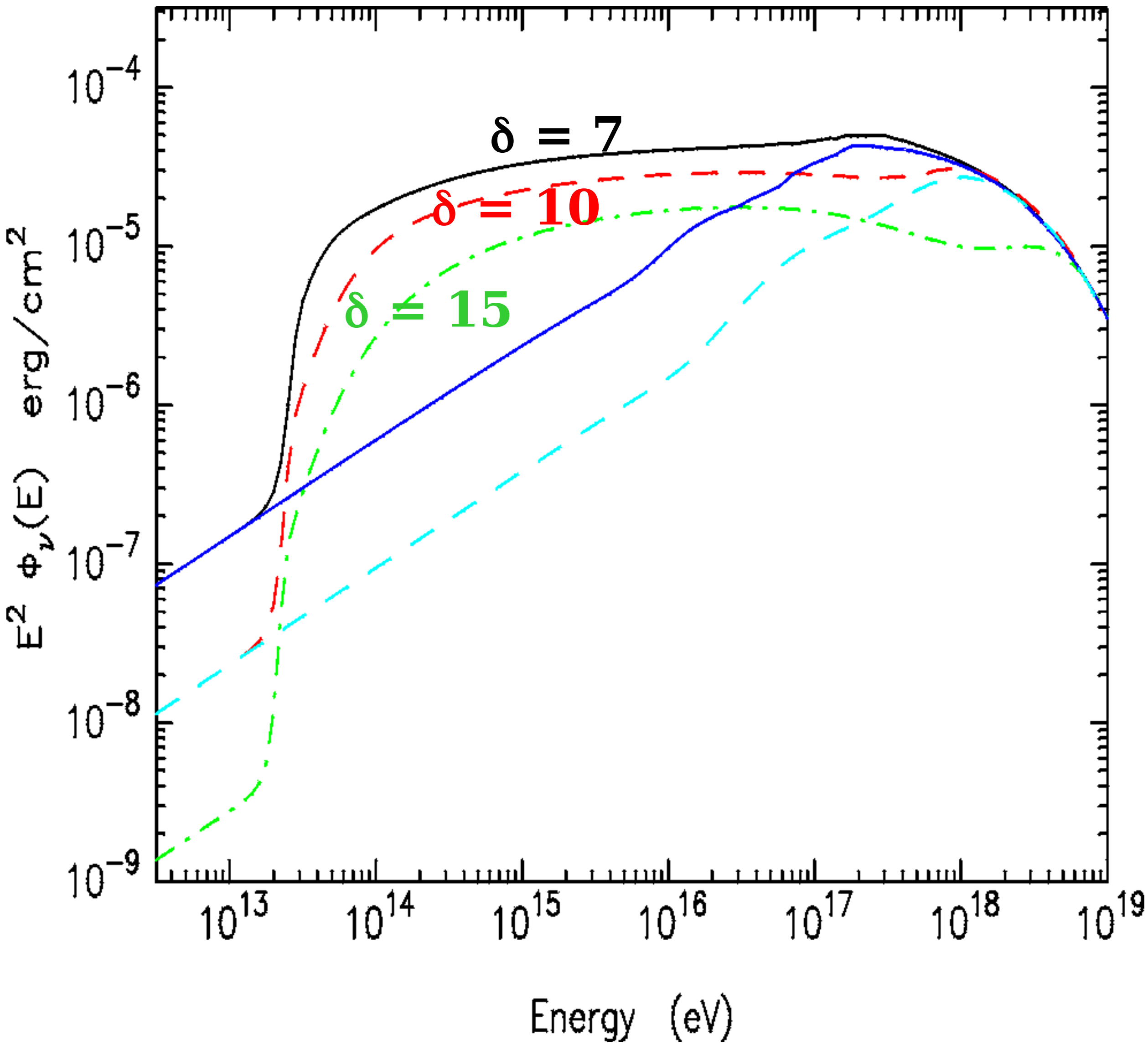
Evolution of the Neutrino Flux

$\delta =$

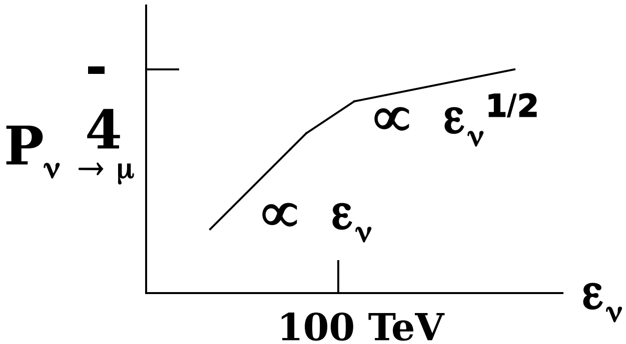


Neutrino Fluences after 3 weeks

Different Doppler factors



- Neutrino fluences from 3C 279 based on 3-week average spectral fluxes observed in 1996 (Wehrle + 1998), with t_{var} = 1 day
- Comparable to the fluence from a bright GRB (different backgrounds)



Gaisser, Halzen, and Stanev 1995

Neutrino detection with km² exposure

Three week average

δ	$N\nu$	N_{max}	t_{var}	B	Wsyn	UV
7	$N\nu$=0.44475	N_{max}=0.78001	t_{var}= 1.00	B= 13.00	Wsyn= 9.53	UV= 190.7
10	$N\nu$=0.27248	N_{max}=0.38583	t_{var}= 1.00	B= 6.70	Wsyn= 1.12	UV= 50.7
15	$N\nu$=0.11995	N_{max}=0.25945	t_{var}= 1.00	B= 3.16	Wsyn= 0.10	UV= 11.2

No external radiation field

δ	$N\nu$	N_{max}	t_{var}	B	Wsyn	UV
10	$N\nu$=0.05436	N_{max}=0.12021	t_{var}= 1.00	B= 13.00	Wsyn= 9.53	UV= 0.0
15	$N\nu$=0.01394	N_{max}=0.02948	t_{var}= 1.00	B= 6.70	Wsyn= 1.12	UV= 0.0

No neutron escape

δ	$N\nu$	N_{max}	t_{var}	B	Wsyn	UV
10	$N\nu$=0.78001	N_{max}=1.04202	t_{var}= 1.00	B= 13.00	Wsyn= 9.53	UV= 190.7

Neutrino detection with km² exposure

Parameters derived from 2 day flare of 3C 279 in 1996;

t_{var} = 1 day

δ	$N\nu$	N_{max}	t_{var}	B	Wsyn	UV
7	0.49389	0.95011	1.00	13.00	9.53	190.7
10	0.34532	0.38963	1.00	6.70	1.12	50.7
15	0.18506	0.27492	1.00	3.16	0.10	11.2

δ 10 — $N\nu$=0.07734 N_{max}=0.13479 t_{var}= 1.00 B= 13.00 Wsyn= 9.53 UV= 0.0

No external radiation field

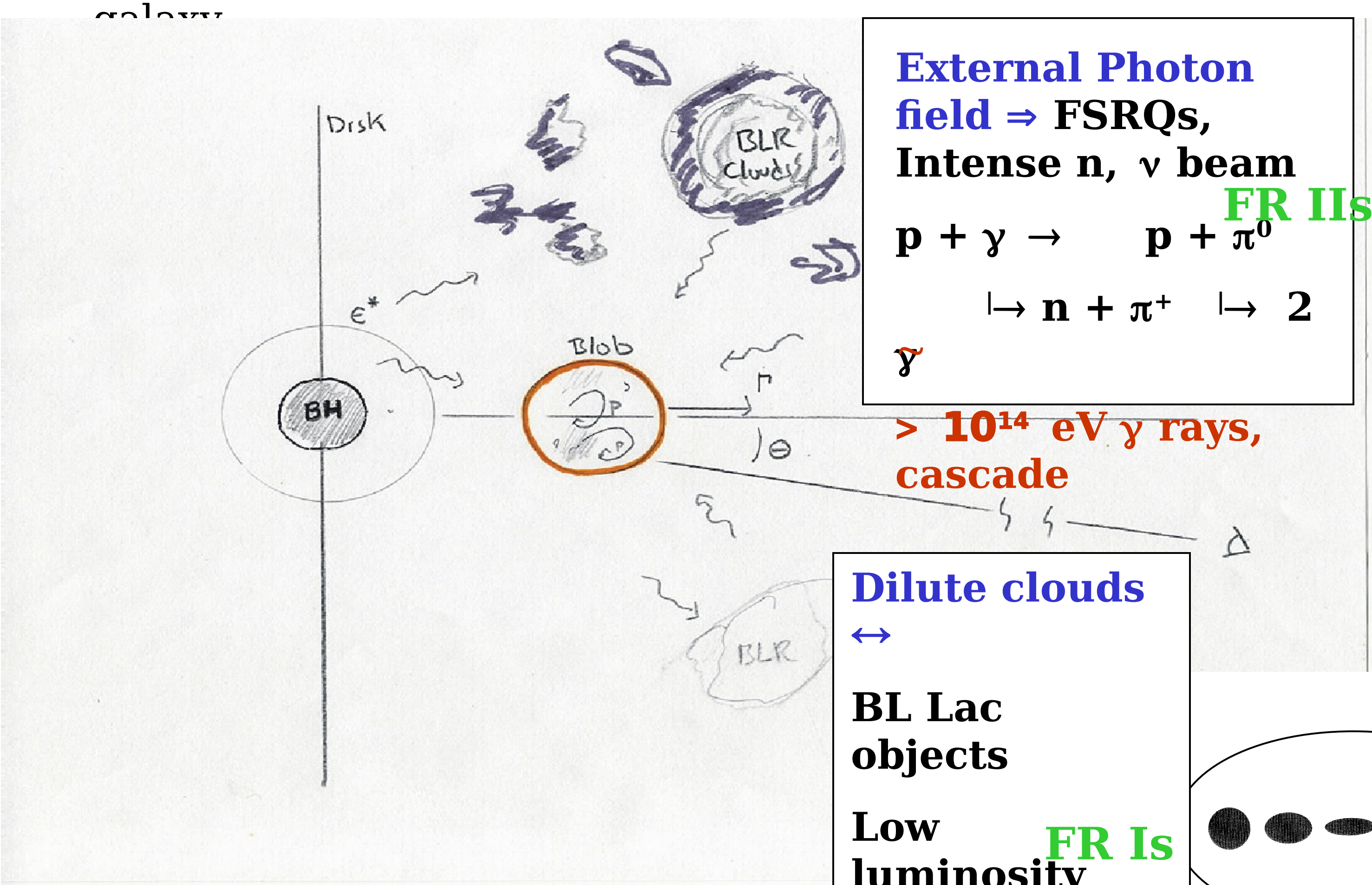
δ 15 — $N\nu$=0.01937 N_{max}=0.03303 t_{var}= 1.00 B= 6.70 Wsyn= 1.12 UV= 0.0

δ 10 — $N\nu$=0.95011 N_{max}=1.04775 t_{var}= 1.00 B= 13.00 Wsyn= 9.53 UV= 190.7

No neutron escape

The Evolution of Active Galaxies

The nuclear activity in a galaxy evolves in response to the changing environment, which itself imprints the spectral energy distribution of the galaxy.



External Photon field ⇒ FSRQs, Intense n, ν beam

FR IIs

$$p + \gamma \rightarrow p + \pi^0 \mapsto 2\gamma$$
$$\mapsto n + \pi^+$$

> 10^{14} eV γ rays, cascade

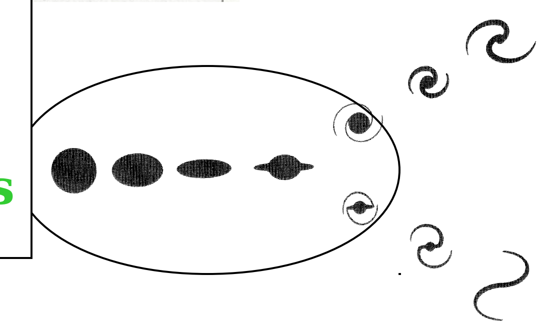
Dilute clouds ↔

BL Lac objects

Low luminosity

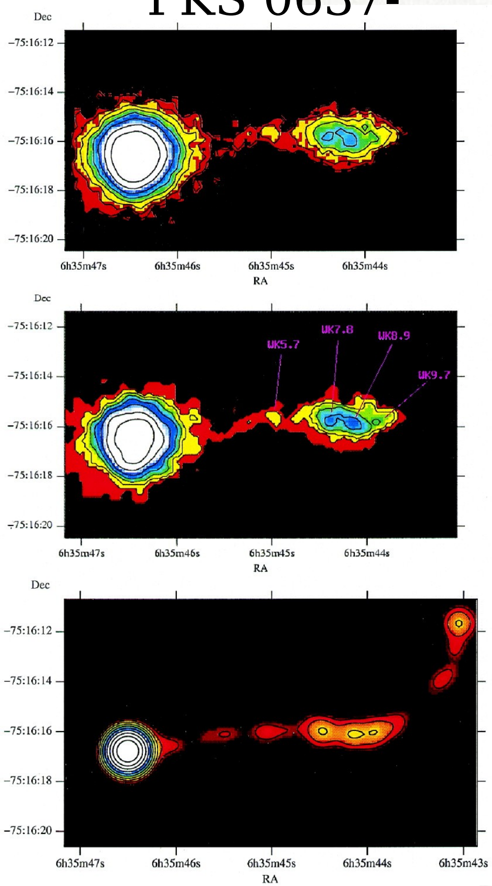
FR Is

Weak jet

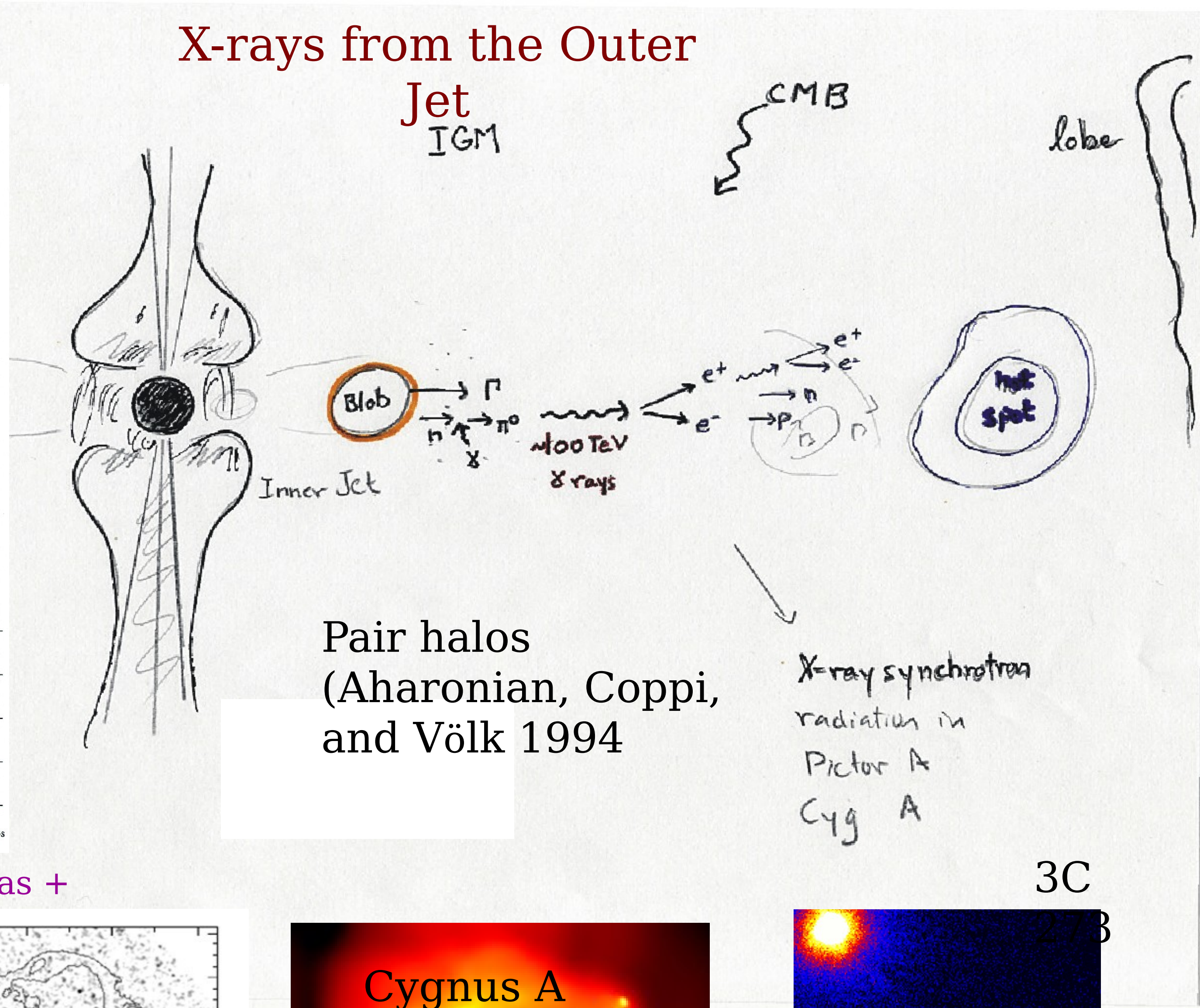


X-rays from the Outer Jet

PKS 0637-

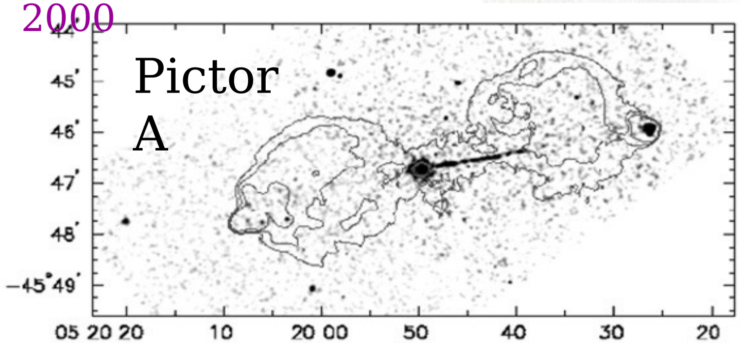


Schwartz + 2000; Chartas + 2000



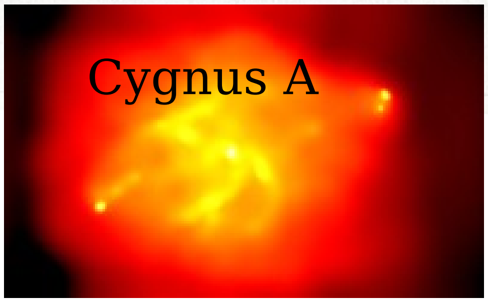
Pair halos (Aharonian, Coppi, and Völk 1994

Pictor A



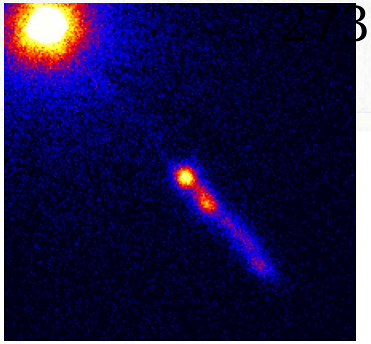
Wilson + 2001

Cygnus A

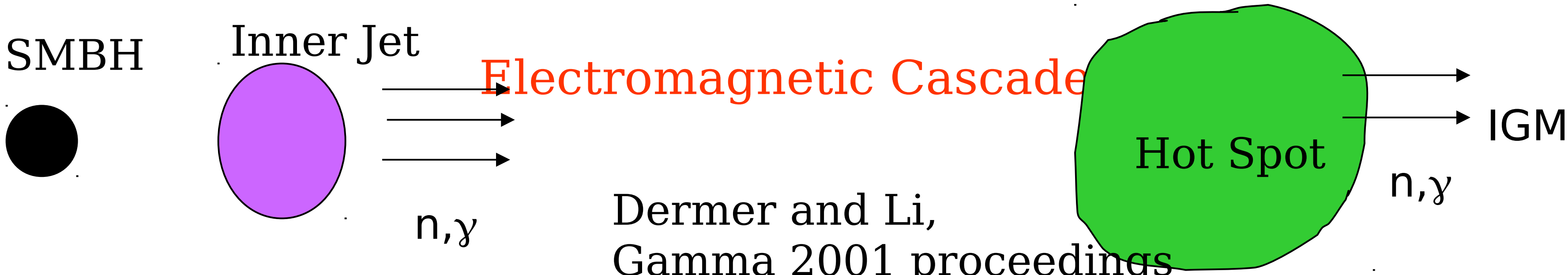


Wilson + 2000

3C 273



Sambruna + 2001



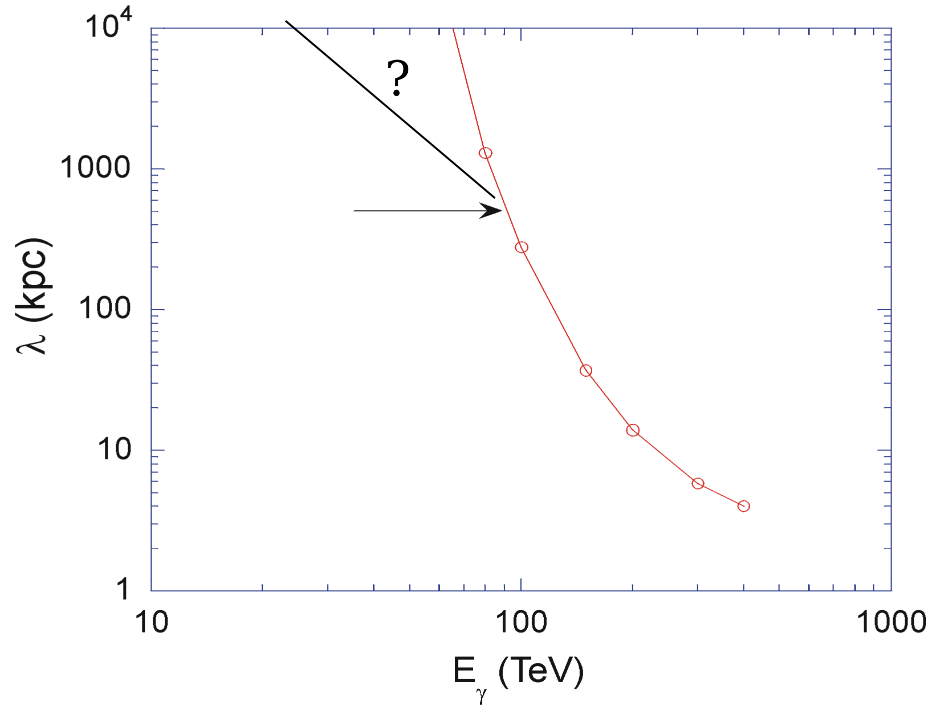
Dermer and Li,
Gamma 2001 proceedings

Photons with energies > 100 TeV are attenuated by CMB and DIIRF background and materialize into e^+-e^- pairs and produces electromagnetic cascade

Neutron beam more highly directed than jet plasma; pre-accelerates IGM in FSRQs;
Difference between FR I and FR II galaxies

Unless $u_B > u_{CMB}$, most of the energy is reprocessed into highly beamed γ rays through Compton scattering, forming pair halos around radio-loud AGN (Aharonian, Coppi, & Völk 1994)

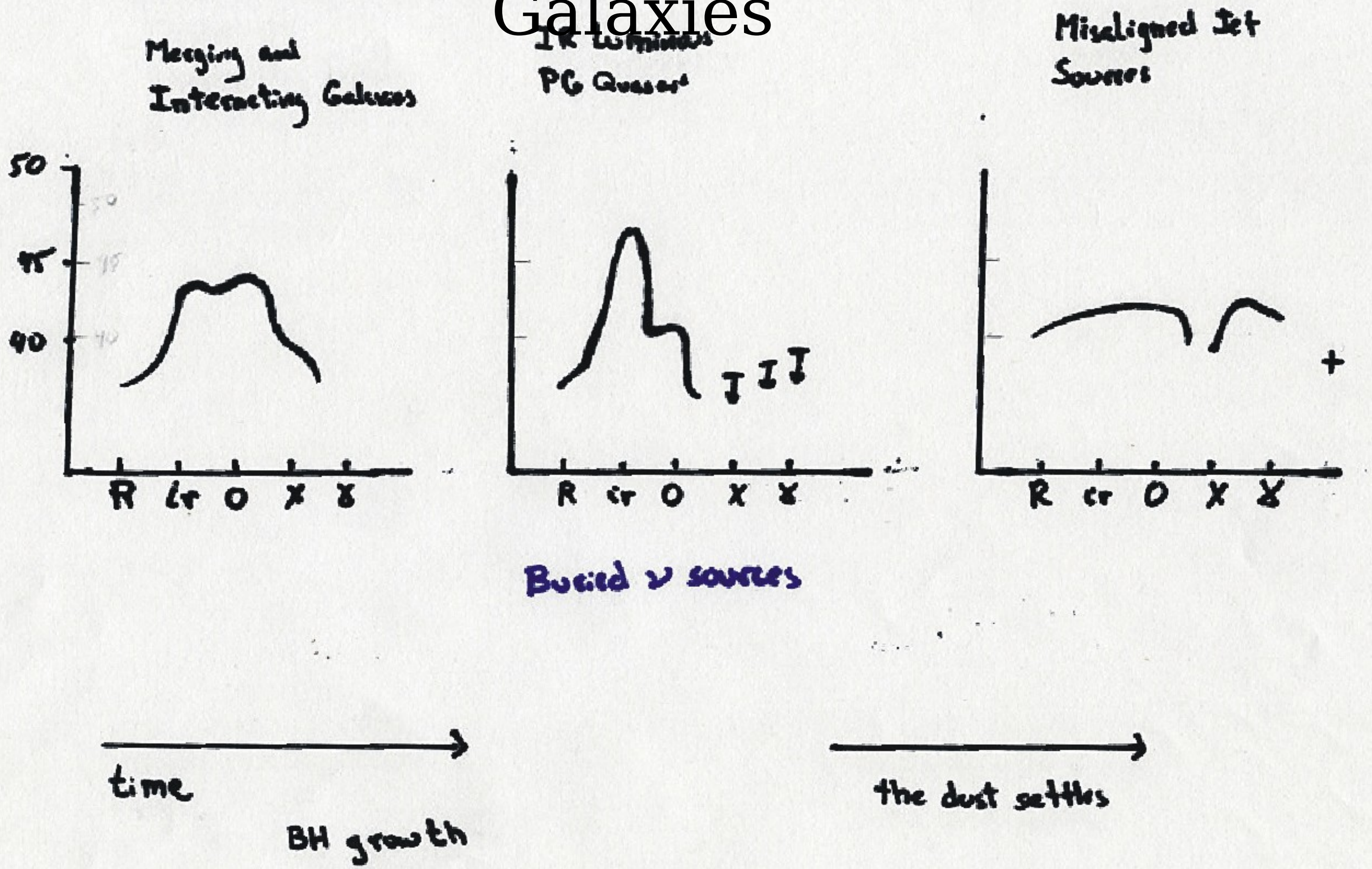
Larger magnetic field in hot spot

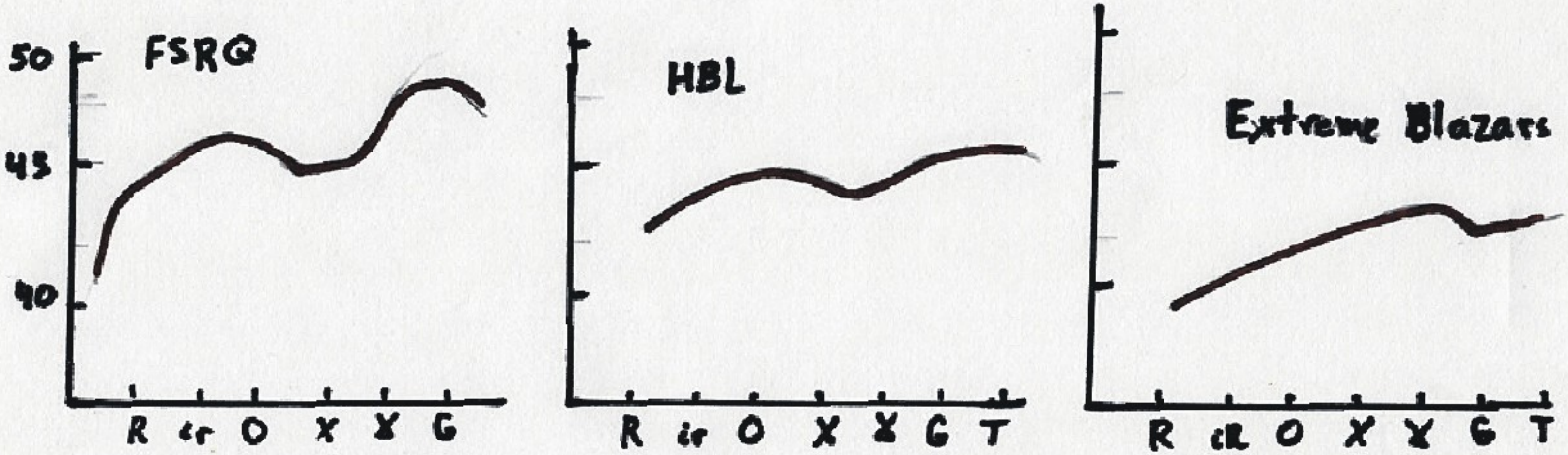


Blazar energy in 30-100 TeV rang
injected into IGM

The End

Evolution of Luminous and Active Galaxies





~ 100 TeV ν Factory

Strong ν source

$\gtrsim 10^{18}$ eV ν Factory

Weak ν source

$M_{BH} > 10^{9} M_{\odot}$

ν Astronomy

High Energy Neutrino Physics

Accelerated p, ion

+

Ambient γ

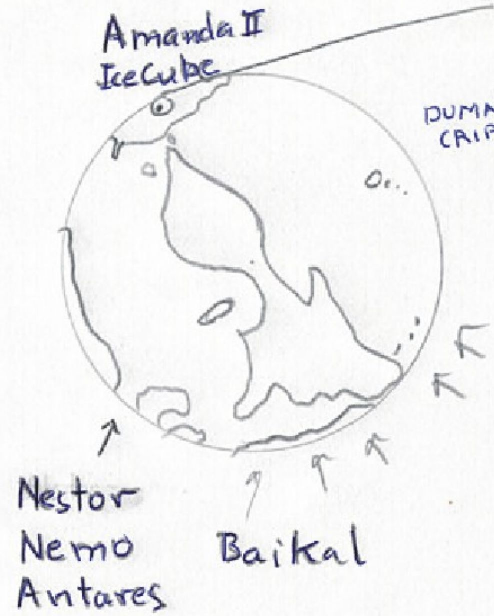
$\downarrow$

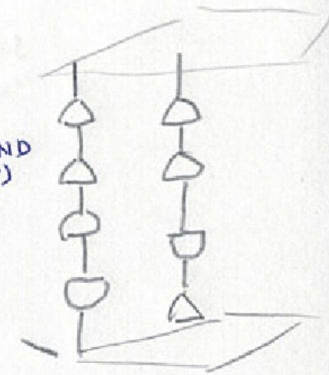
$p + \pi^0$

$\hookrightarrow 2\gamma$

$n + \pi^+ \to \mu^+ + \nu_\mu$, $\quad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$

$\hookrightarrow p + e^- + \bar{\nu}_e$





$\nu_\mu + N \to \mu + \text{anything}$

ff

μN

$\to e^+e^-$

ionization losses